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Experimental methodology for characterizing flame emissivity of small scale forest fires using infrared thermography techniques

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ABSTRACT: An experimental methodology based on thermography techniques has been developed and implemented with the aim of finding emissivity values of forest fuel flames. In this paper, previous works by different authors are discussed and theoretical fundamentals of heat transfer by radiation and of infrared thermography on which experimental method relies are briefly described. Then, designed methodology, equipments, devices and experimental tests are detailed in depth. Finally, analysis procedure is pointed out and some conclusions from the study of the results are announced.

1 INTRODUCTION: FLAME EMISSIVITY IN FOREST FIRES

Radiation emitted by the flames, which is covered in the visible region and mainly in the infrared region (between 1 μm and 6 μm) of the electromagnetic spectrum, comes from hot gases —CO_2 and H_2O— and carbonaceous solid particles of incandescent soot. It originates throughout the flame, which is considered transparent to its own radiation to a certain thickness. Hot gases emit radiation in particular bands of the infrared spectrum. The highest emission of CO_2 is located at 2.7 μm and 4.4 μm and the maximums of H_2O are at 1.4 μm, 1.9 μm and 2.7 μm. However, soot particles emit radiation in a continuous spectrum over a wider region from the visible to the infrared, and the more the wavelength increases, the greater the drop in radiation intensity (Sato et al., 1969). Nevertheless, this reduction in intensity is omitted by the majority of authors (Draysdale, 1997); according to their approach, soot particles and flames generally are considered to be gray or black bodies. Following this simplification, and considering an average temperature of the flame, Stefan-Boltzmann's equation is used to determine radiation intensity. This intensity may be separated into two different compounds, which are the partial contributions of hot gases and soot:

$$I_f = \varepsilon_f \sigma T^4 \tag{1}$$

$$I_f = I_s + I_g - I_{sg} \tag{2}$$

$$I_f = \varepsilon_s \sigma T^4 + \varepsilon_g \sigma \cdot^4 - \varepsilon_s \varepsilon_g \sigma T^4 \tag{3}$$

where I_f = flame radiation intensity, W/m^2; ε_f = flame emissivity, -; σ = Stefan-Boltzmann constant, 5.67 · 10^{-8} W/m^2·K^4; T = temperature, K; I_s = soot radiation intensity, W/m^2; I_g = gas radiation intensity, W/m^2; I_{sg} = radiation exchange between soot and hot gases, W/m^2; ε_s = soot emissivity, -; and ε_g = gas emissivity, -.

The emissivity of flames which have little soot is less than the emissivity of flames producing more soot particles. Soot must therefore be considered as responsible for very luminous flames having high emissive power, which is superimposed on the emissive power of the molecules of H_2O and CO_2. In this way, it is considered that flames with a high production of soot have a high emissivity and lose much energy by radiation, which means that the average temperatures in this type of flames are lower than in flames with less soot (Draysdale, 1997).

Flame radiation intensity depends on its composition and on the concentration of its molecules along its optical path. What can be gathered from this is that flame emissivity is strongly conditioned by its thickness, by its regime and conditions of combustion and by the composition and the type of fuel burned. With an efficient mixture of fuel and air, soot production is minimal and a less radiant and bluish flame appears, with very high temperatures. Flames from the combustion of methanol with an emissivity of 0.07 reach an average temperature of 1200 ºC (Rasbash et al., 1956). However, incomplete combustion, due to a defective mixture of fuel and comburent or due to a lack of comburent, causes the formation of small particles of carbon, which make up soot. Flames produced in this situation are yellowish and orangish and have very high emissivity but a lower temperature. In Quian and Saito (1995), hexane flames of 20 cm of thickness reached emissivity values of about 0.8 with mean temperatures between 700 ºC and 800 ºC. Also, a progressive increase in emissivity with the diameter of the flame in laminar and transition regime was demonstrated. Chatris (2002) tested with greater thicknesses, up to 50 cm, which were representative of the turbulent regime. This author obtained emissivity values of around 0.85 from gasoline and diesel flames, and maximum temperatures of around 750 ºC.

In forest fires, typical flames are turbulent and they have an intense luminosity due to their great amount of soot. They are diffusion flames, which means that fuel gases and air are initially separated and combustion occurs in the place where these are mixed. However, the great variability of the conditions that influence the spread of a forest fire —weather, fuel, topography— determines the appearance of equally variable flames, which develop in transition regime most of the time and which have highly fluctuating emissivity and temperatures. Changes in wind velocity and direction and in fuel distribution determine the supply of air in the combustion and thus its efficiency, causing the appearance of flames with higher or lower emissivities. Moreover, the chemical composition of forest fuel, which is different for each species, has an influence on flame characteristics. Species releasing a great amount of volatile material during the pyrolysis process burn with very luminous flames with high soot concentration (Ventura et al., 1998). Fuel moisture content also affects the emissive power of flames, due to its influence on both emissivity and temperature. King (1973) studied this matter and came to the conclusion that the higher the fuel moisture content, the higher the partial contribution of radiation from gases compared to soot contribution, which may be interpreted as meaning that emissivity decreases with fuel moisture.

In spite of such a large number of conditioning factors, several authors have tried to characterize the emissivity of flames resulting from the combustion of biomass and they have studied the effect of some variables on this parameter. Beyreis et al. (1971) performed a series of small scale tests in a combustion chamber with the aim of quantifying emissivity in wood crib fires and studying its evolution with flame thickness. Flame radiation was measured by a thermopile of 6 cm of diameter, which was placed at a horizontal distance of 120 cm from the fuel and at a variable vertical distance, between 30 cm and 120 cm, following the evolution of the fire. This vertical distance was also the reference for placing the thermocouple, which was immersed in the flame in order to obtain its temperature. Flame thickness was observed through a slot in one wall of the chamber.

These parameters were recorded during the steady state —between 7 and 10 minutes— of 5 experimental tests which had different fuel loads. Temperature values between 650 ºC and 1300 ºC were obtained with flame thickness between 25 cm and 190 cm. Flame emissivities were also located in a wide range, between 0.1 and 0.6. A single expression for emissivity with thickness was developed from the data of all the tests:

$$\varepsilon_f = 1 - e^{-0.51x} \tag{4}$$

where x = flame thickness, m.

Later, Hägglund and Persson (1976) carried out a similar but more complex experimentation. A total of 16 tests of wood crib flames were performed in an asbestos enclosure. Temperature, flame thickness and radiation were also measured. The technique used to record this last parameter was different from that used by Beyreis et al. (1971). A single-beam double-pass prism spectrophotometer captured spectral distribution of flame radiation at 2 specific heights, at 30 cm for the first 11 tests and at 50 cm for the last 5. Flame radiation intensity was then obtained by numerical integration. Although these authors also worked with thermopiles in certain tests, obtaining identical results, the use of the spectrophotometer allowed them to make a deeper and more exhaustive study of the partial contributions of radiation of the different components of the flame. Temperature and flame thickness were recorded by identical methods to those used in Beyreis et al. (1971). The numerical values of the observed parameters during the steady phase of combustion were equally located in similar ranges. In Hägglund and Persson (1976), flame thickness ranged from 15 cm for smaller fires to 200 cm for larger ones. Temperature varied in a similar way, between 650 ºC and 1030 ºC. Calculated emissivities reached values close to unity in some tests, ranging between 0.12 and 0.94. The emissivity function proposed by these authors is:

$$\varepsilon_f = 1 - e^{-0.8x} \tag{5}$$

Furthermore, the authors reached some conclusions arising from the study of the electromagnetic spectrum. They observed that in thin flames, band radiation, which was originated by hot gases, was the dominant radiation, above continuous radiation emitted by soot particles. However, in thicker flames, the soot contribution was considerably higher than the gas contribution.

Despite the attainment of expressions (4) and (5) derived from these experiments, with which emissivity values may be easily calculated, the scientific and experimental methodology of both cases has some restrictions which strongly condition the use of these equations. The most notable simplification, which was adopted in both studies, was the use of an average flame temperature by particular values from thermocouples, which were located at given points in a certain region. As a result of this situation, some inconsistencies arose in Hägglund and Persson (1976). In one of their tests, flame radiation described a curve of spectral distribution, which was slightly superimposed on the curve of black body radiation, at the mean temperature adopted in that case. From this it may be deduced that temperature in the particular region observed by the spectrophotometer was higher than the mean temperature calculated by the thermocouples.

This simplification affected both the data analysis and their mathematical treatment. Equations were treated as representative expressions of the behavior of the whole flame. However, these expressions came from the graphical study of some points positioned in a small region of the flame, which undoubtedly had particular properties different to the rest of the regions, due to the variability of temperature, thickness and emissivity throughout the flame. In Hägglund and Persson (1976) these points were located at 30 cm and 50 cm. These authors did not detect many variations between the spectrums at these different heights. Nevertheless, Beyreis et al. (1971) used different points randomly located at 4 vertical distances, 30 cm, 60 cm, 90 cm and 120 cm, with which a single expression was obtained. Emissivity differences with height may be observed in data mentioned by the authors, but they have not been considered in any case.

The characteristics of the fuel used in these experiments should be mentioned. Although it was made of wood cribs of *Picea excelsia*, it is not very representative of forest fuel, which has a very variable moisture content due to weather conditions, and which presents an irregular morphology and composition throughout its equally variable land distribution. The only expressions from the bibliography drawn exactly from forest fuels were Telisin's (1974) and Thomas' (1971) equations. Telisin (1974) used data obtained in experimental tests, which were collected by Wolliscroft (1968, 1969a, 1969b). In these works, rate of spread, height and flame thickness, temperature and radiant energy were measured in a fire front, which was moving down a fuel bed composed of oak leaves. Packing ratio and moisture content were also recorded. In Wolliscroft (1968, 1969a, 1969b) attention was drawn to the effect of moisture content on flame emissivity. The extinction coefficient was 0.15 for a fuel moisture content of 12%, and when moisture content reached 34% the extinction coefficient rose to 0.17. For identical flame thicknesses, this factor results in a slight increase in emissivity, which contradicts King's (1973) assertion. The Telisin (1974) equation of emissivity with flame thickness has an extinction coefficient lower than Equations (4) and (5):

$$\varepsilon_f = 1 - e^{-0.16x} \qquad (6)$$

Previously, Thomas (1971) obtained a similar expression using data from burns of heathland and gorse. In these experiments, geometric features of flames were measured by a photographic study of the fire front. Temperature and heat fluxes were also recorded by radiometers and thermocouples. Thomas (1971) proposed two different equations for emissivity following the inclination of the flames; one for vertical flames and another for flames with a certain inclination due to the effect of wind:

$$\varepsilon_f = 1 - e^{-0.1x} \qquad (7)$$

$$\varepsilon_f = 1 - e^{-0.3x} \qquad (8)$$

Expressions (4), (5), (6), (7) and (8) have been evaluated by various authors. Butler (1993), in his experimental work studying heat flux by radiation in laboratory fires of *Pinus pinaster* needles and *Populus tremuloides* excelsior, obtained flame emissivities which agree with Telisin (1974). Quintiere (1998) took into consideration Hägglund and Persson's (1976) work, when he asserted that emissivities close to unity might be found in typical forest fire flames of 2 m of thickness. However, Chandler (1983) stated that flames of lower thicknesses could have emissivities close to the value assigned to black body radiators.

Due to these disagreements, there is no single criterion for fitting values of emissivities in theoretical forest fire spread models in which radiation has been taken into account. Pagni and Peterson (1973) adopted typical values of flames originating from the combustion of cellulosic material, which ranged from 0.15 to 0.30. Likewise, Anderson (1969) used similar values, between 0.16 and 0.28. Cohen and Butler (1998) were more conservative. They modeled the heat flux emitted by a fire front burning in the wildland/urban interface and they considered flame emissivities equal to unity. Several authors left out this parameter due to the difficulty in obtaining correct values of it. Therefore, they opted to model the heat transfer by radiation in a fire front with an all-inclusive estimation of its emissive power (Albini, 1985, 1986; Dupuy 1997; Porterie et al., 1998). All these examples illustrate that it is necessary to obtain data for the physical parameters which take part in the heat transfer of a forest fire front —emissivity among them— because they are unavoidable inputs in forest fire spread models in which conduction, convection and radiation are entirely taken into account.

Due to all these considerations and due to the need to know target emissivity when working with infrared cameras for forest fire analysis, an experimental methodology based on thermography techniques has been developed and implemented with the aim of finding emissivity values for forest fuel flames. In the following section, its main features, the theoretical principles on which the methodology is based and the equipment used are all detailed. Then, the steps making up the data analysis are listed and the results of 4 pilot tests, which were carried out to validate the methodology, are briefly discussed.

2 METHODOLOGY

Emissivity determination was carried out by means of a methodology based on techniques of infrared thermography. An IR camera, which captures thermal radiation emitted by a target, was used. By fitting a known or supposed emissivity value, thermal images with a temperature value for each pixel are obtained. The main specifications of the IR camera are included in Table 1.

Table 1. Main specifications of the IR camera.

Characteristic	Value or description
Object temperature measurement range	253 K - 1773K
Measurement accuracy	± 2 % of range
Thermal sensitivity	< 0.15 K
Detector type	Focal Plane Array (FPA) uncooled
Spectral range	7.5 µm - 13 µm
Integration time	15 ms
Distance range between camera and object	0.5 m - 100 m
Ambient temperature range at filming time	258 K - 323 K

Flame emissivity may be determined using an IR camera by two different methods:

a) By measuring the temperature of one point of the flame using a thermocouple or any other temperature measurement system by contact. Once this point temperature is known, it is also measured by the IR camera and the emissivity value must be modified until the IR camera and the thermocouple values coincide. This is a very easy method from a conceptual point of view, but it involves a series of difficulties and limitations, which are related to the fact that the temperature at any given point of the flame is continuously changing and, therefore, it is very complicated to fit the value of emissivity in real time. Moreover, the response time of the two systems is very different, which makes the situation worse. Finally, the measurement of the thermocouple is on a point basis whereas the camera provides an average value for the surface temperature with a certain depth.

b) By determining flame transmissivity. As flame reflectivity is equal to zero, emissivity may be estimated by measuring the fraction of energy transmitted by the flame, which comes from a black body ($\varepsilon = 1$) with a known temperature. Considering the partial contributions of radiation with regard to the total radiation captured by the IR camera, which are the energy emitted by the flame and the energy that it transmits from the black body placed behind it (Figure 1), an expression of flame emissivity may be obtained (Planas-Cuchi et al., 2002) following this development:

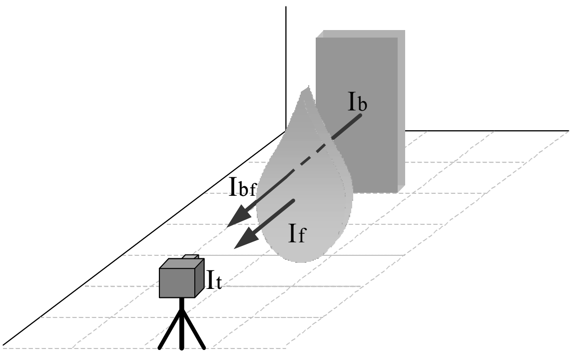

Figure 1. Schematic diagram of methodology b) for the experimental determination of flame emissivity

$$I_t = I_f + I_{bf} \quad (9)$$

where I_t = total radiation intensity, W/m^2; I_f = flame radiation intensity, W/m^2; and I_{bf} = radiation intensity transmitted by the flame, W/m^2.

Considering flame transmissivity, Equation (9) is expressed thus:

$$I_t = I_f + \tau_f I_b \quad (10)$$

where τ_f = flame transmissivity, -; and I_b = blackbody radiation intensity, W/m^2.

Applying Stefan-Boltzmann's Equation (1), Equation (10) is converted into the following expression,

$$\varepsilon_t \left[(T_t(\varepsilon_t))^4 - T_a^4 \right] = \varepsilon_f \left[(T_f(\varepsilon_f))^4 - T_a^4 \right] + (1 - \varepsilon_f)\varepsilon_b (T_b^4 - T_a^4) \quad (11)$$

where ε_t = flame emissivity combined with the blackbody emissivity, -; $T_t(\varepsilon_t)$ = flame temperature combined with blackbody temperature, which is function of ε_t, K; T_a = ambient temperature, K; ε_f = flame emissivity, -; $T_f(\varepsilon_f)$ = flame temperature, which is function of ε_f, K; ε_b = blackbody emissivity, -; and T_b = blackbody temperature, K.

To obtain the parameters included in Equation (11), an experimental methodology was designed in which a series of tests with forest fuels were carried out in order to determine flame emissivity with flame thickness. The arrangement of the equipment may be observed in Figures 2a and 2b. In addition to the IR camera, with which the temperature distributions of each experiment were obtained, two video cameras were used. The first one was positioned beside the IR camera in order to compare thermal and visible images. The second video camera was placed in a perpendicular direction to the first, with the aim of recording the experiment laterally and extracting the flame thickness. Two K thermocouples, which were placed at 1/4 and 3/4 of the total height of the flame, measured blackbody temperature, which was reproduced by a smoked aluminum plate 80 cm high and 1 mm thick, with an emissivity close to one (ε = 0.95). This black body was placed behind the combustion table, whose dimensions are 1 m x 1 m.

This methodology was tested by performing 4 tests, in which fine forest fuel with a timelag lower than 1 hour was burned. The main features of these tests are detailed in Table 2.

Table 2. Main features of experimental tests

Tests	Fuel species	Arrangement of the fuel bed		Moisture content (%)
		Dimensions (cm)	Density (humid weight, kg/m^3)	
Test 1	*Pinus halepensis*	25 x 25	3.3	40
Test 2	*Pinus halepensis*	50 x 50	1.6	50
Test 3	*Pinus halepensis*	100 x 100	1.1	60
Test 4	*Rosmarinus officinalis*	50 x 50	2.4	80

The fuel used in 3 of the 4 tests was needles and fine branches of *Pinus halepensis*. This species is representative of the vegetation of the Mediterranean, and especially that of our country. In the last test, a different fuel, also very typical of the Mediterranean Basin, was burned in order to contrast results of two different species.

The fuel beds were overloaded to guarantee long fires with persistent flames and also to counteract high moisture contents. The dimensions of the 4 tests were 0.0625 m^2 (tests 1 and 4), 0.25 m^2 (test 2) and 1 m^2 (test 3), with which maximum flame thickness of 25 cm, 50 cm and 100 cm respectively were observed.

3 EMISSIVITY DETERMINATION

To obtain emissivity values for the 4 tests, a methodology for analyzing thermal images was designed. This methodology was used to deduce $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$, which are the basic parameters of Equation (11). With the rest of the variables measured experimentally, this equation was solved graphically. The values of ε_f were compared with flame thickness in each test.

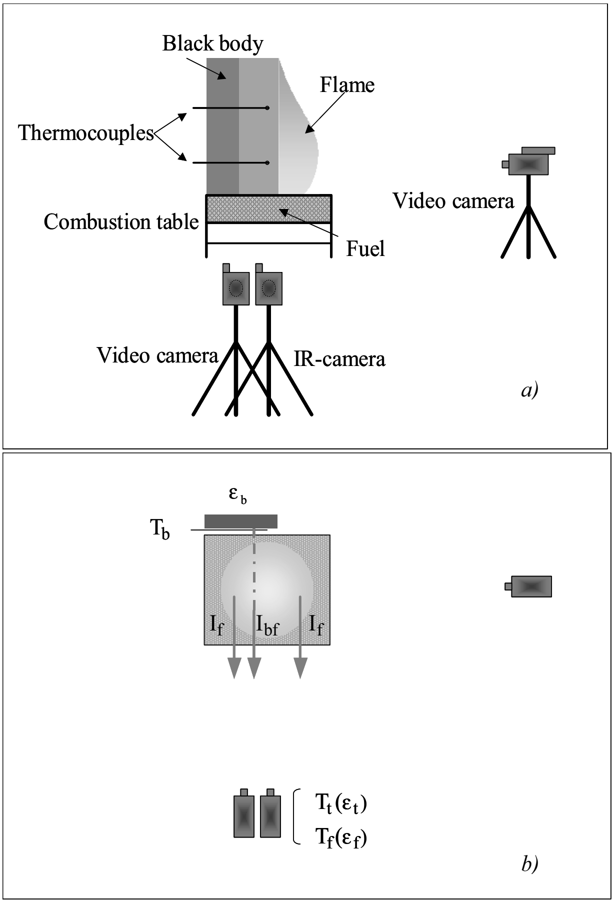

Figure 2. Views of experimental devices a) Elevation b) Plan

Previously, it had been necessary to carry out an initial test with the aim of comparing the two different temperature measurement systems, the IR camera and the thermocouples. During this test, T_b at 1/4 and 3/4 of the black body height was recorded by the thermocouples and, at the same time, thermal images of the smoked aluminum plate were obtained. Data analysis showed the thermal images to have of slightly higher and more variable temperature values than those obtained by the thermocouples. This is due to the difference between the response times of the two systems as mentioned above, and also to the difference between the mechanisms for obtaining temperature: conduction for the contact system and radiation for the IR camera. Nevertheless, measurements of blackbody temperature by thermocouples are considered valid. Moreover, it has to be taken into account that the method of calculation which has been developed is not very sensitive to changes in T_b, because of the little weight of the last addend of expression (11) in comparison with the terms made up of the functions $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$.

3.1 *Analysis of thermal images*

The IR camera used records thermal images at a rate of 1 frame per 2 seconds and it stores them on a PCMCIA card, from which the information is transferred to the computer. The thermal images were studied by 2 specific software programs, namely the Thermacam Explorer 99 and Thermacam Researcher 2001. The first program allows images to be seen easily and quickly and thus they may be classified and selected before the analysis. In this way, thermal images representing the steady phase of each test were selected, and the images representing the transient regime of ignition and extinction, in which the abundance of smoke makes analysis impossible, were rejected.

The second program is used for in-depth study of thermal images, and it allows information on different thermal parameters to be manipulated. It should be pointed out that, in addition to emissivity, an IR camera needs other parameters to be adjusted for the correct calculation of temperature, such us relative humidity, ambient temperature, which is also used in Equation (11), and distance between the IR camera and the target. All these were experimentally measured in several tests.

The aim of analyzing thermal images was to find the expressions of $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$ of the images which were previously selected. For each one, 4 areas of study were established, two areas in the left half of the images (A_{lu} and A_{ld}), which were centered at 1/4 and 3/4 of the total height of the blackbody, and the others symmetrically in the right half of the images (A_{ru} and A_{rd}), considering the symmetry axis on the right edge of the blackbody (Figure 3).

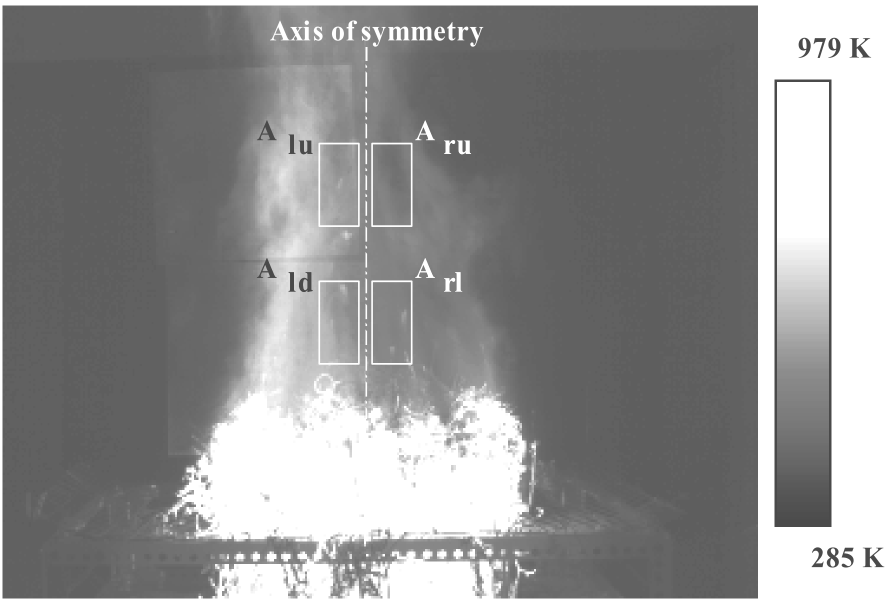

Figure 3. Position of the four different areas on a thermal image of the test 4.

By changing the emissivities of the areas (ε_t, for the sections placed to the left of the axis and ε_f for the sections placed to the right of the axis) different mean temperature values of the four areas were obtained. The dependence of these parameters follows a power law with a correlation coefficient very close to unity. In Figure 4, $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$ corresponding to A_{lu} and A_{ru} for a thermal image of test 1 are graphically represented.

Analyzing the two curves $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$ of every image selected from the different tests, it can be observed that the thicker the flame, the lower the separation between the curves, and therefore, the higher the emissivity. Moreover, the decrease in emissivity with flame height is also visible. By representing the two pairs of curves of any given image, it may be noticed that upper areas are separated by a wider gap, and they are represented below lower areas, which have higher emissivities.

This methodology of thermal analysis was compared with a set of images selected at random from tests 1, 2 and 3. With the aim of testing whether $T(\varepsilon)$ is really characteristic of the mean temperature of the areas drawn, which are around 100 cm^2, we calculated the standard deviation of the emissivities of 4 divisions measuring 25 cm^2, which were marked out for the initial sections. In all the cases, these deviations were sufficiently low to consider $T(\varepsilon)$ a representative function of the mean temperatures of the areas designated.

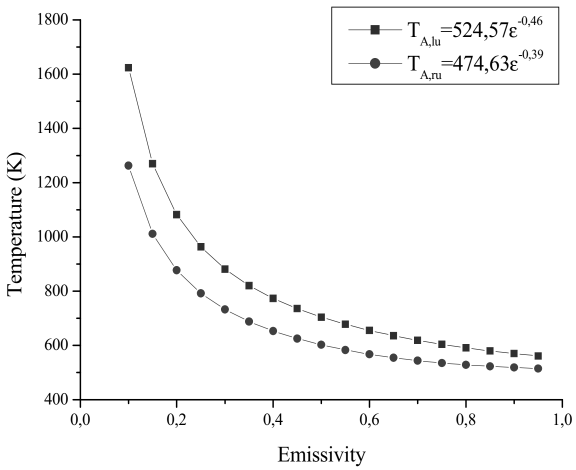

Figure 4. Variation of mean temperature of A_{lu} and A_{ru} with the emissivity for an image of test 1.

3.2 *Resolution of equation (11)*

Once $T_f(\varepsilon_f)$ and $T_t(\varepsilon_t)$ were found and ε_b, T_a and T_b were known, Equation (11) was solved graphically. All the terms were placed on the same side of the equation and, by supposing a certain ε_t, the value of ε_f for which the resultant function is equal to zero was obtained.

In order to make an estimation of ε_t, it was taken into account that ε_f will always be lower than ε_b and also that ε_t will always be higher than ε_f and than $(1-\varepsilon)\varepsilon_b$ (Planas-Cuchi et al., 2002). By showing the equation on a graph for different values of ε_t, it was observed that these conditions are fulfilled by $\varepsilon_t > 0.7$. Therefore, it is considered that $\varepsilon_t = 0.85$, which is the average between 0.7 and the emissivity of the smoked aluminum plate ($\varepsilon_b = 0.95$).

This procedure was carried out twice for all the thermal images selected for each test. In this way, two series of emissivity values of each experiment were obtained: the first one related to 1/4 of the total flame height, and the second one related to 3/4 of the total flame height.

4 RESULTS

The emissivity values related to flame thickness are the average values of both series for the different tests. They are represented together with expressions by various authors, as mentioned in Figure 5.

Although they are purely illustrative, the experimental results show that the increase in emissivity with flame thickness is more marked in the tests carried out than in the expressions found in the bibliography. Likewise, they confirm Chandler's (1983) assertion, in which he says that emissivities close to unity may be found in flames of forest fires with thicknesses lower than the values proposed in the literature. The figure mentioned above shows the curves correlating experimental data, obviously taking into account the differences in design between all the tests performed. The equation of emissivity at 3/4 of the total flame height is expressed as:

$$\varepsilon_f = 1 - e^{-2.24x} \tag{12}$$

Likewise, the equation of emissivity at 1/4 of the total flame height is expressed thus:

$$\varepsilon_f = 1 - e^{-3.11x} \tag{13}$$

The correlation coefficients obtained are around 0.95 in both cases.

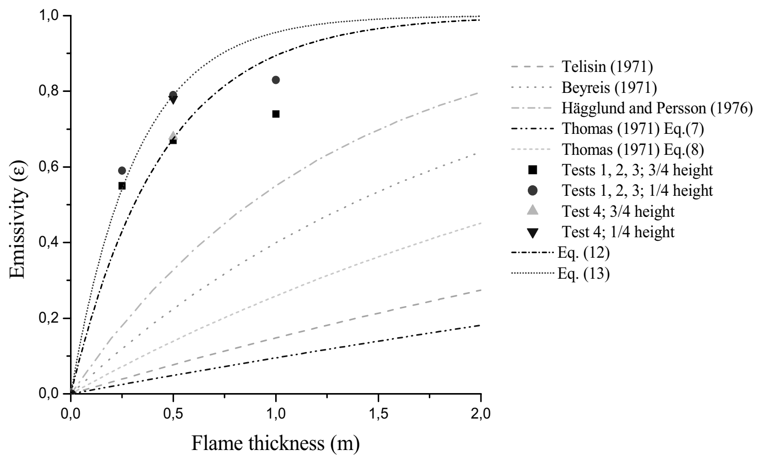

Figure 5. Comparison of the experimental values with the expressions mentioned in the literature.

5 CONCLUSIONS

An experimental methodology for obtaining flame emissivity in the combustion of forest fuels has been developed, based on techniques of infrared thermography.

This methodology has been successfully implemented, by means of 4 pilot tests with typical species of Mediterranean vegetation. With the results extracted from these tests, the dependence of flame emissivity on flame thickness has been observed. The variability of flame emissivity with flame height has also been detected. This consideration has not been taken into account in the majority of previous studies.

Two experimental correlations have been proposed. They relate flame emissivity with thickness at two different heights of the flame.

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